STATUS OF MAGNETIC SUSPENSION TECHNOLOGY

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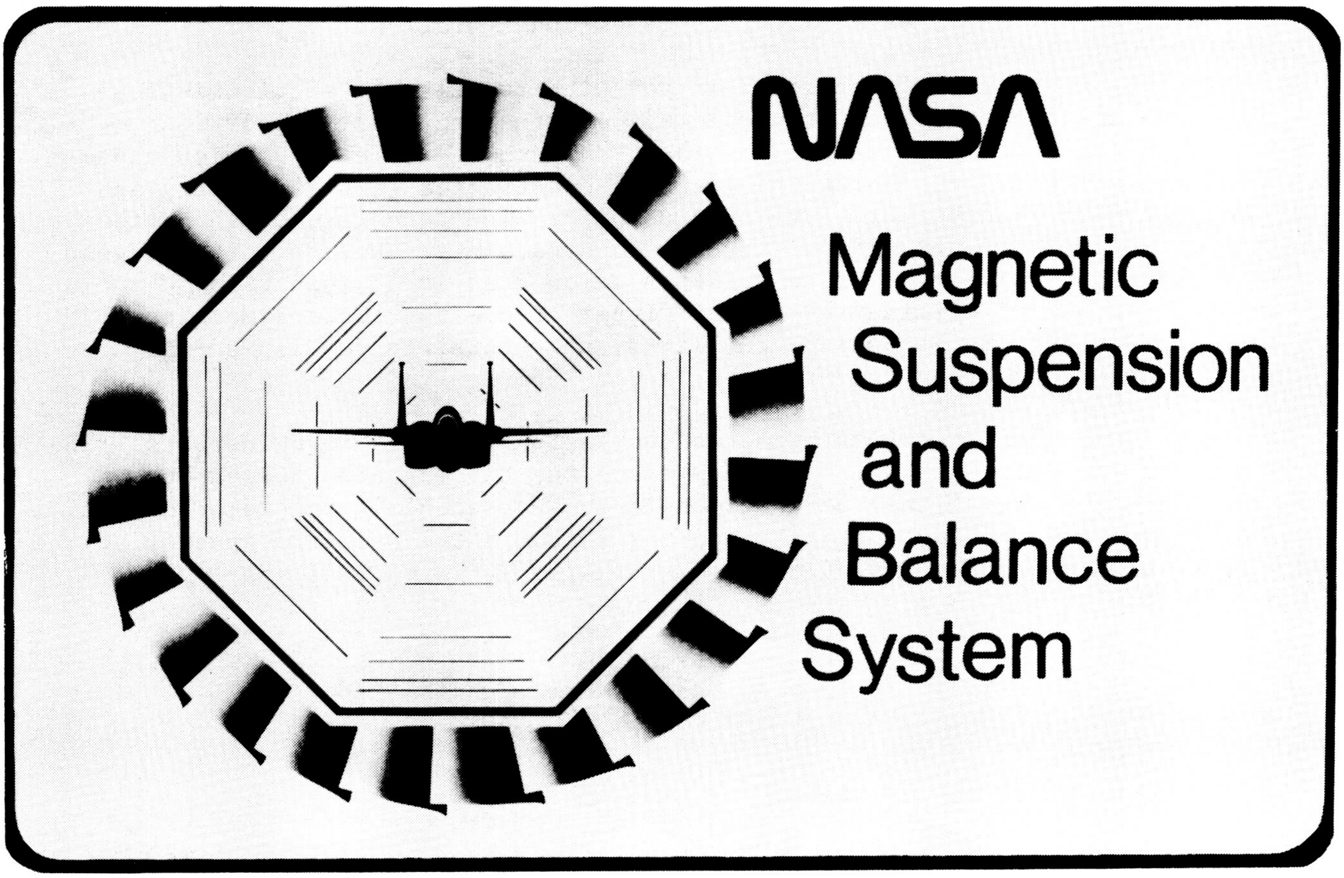
ABSTRACT

This paper highlights the reasons for the continuing interest in Magnetic Suspension and Balance Systems (MSBS). Typical problems that can arise because of model-support interference in a transonic wind tunnel are shown to illustrate the need for MSBS. The two magnetic suspension systems in operation at Langley are the only ones active in the U.S. One of these systems is the 13-inch MSBS which was borrowed from the Air Force Arnold Engineering Development Center. The other system is the 6-inch MSBS which was developed by the MIT Aerophysics Laboratory with NASA and DOD funding. Each of these systems is combined with a subsonic wind tunnel. Ongoing research in both of these systems is covered. Last year, Madison Magnetics, Inc., completed a contractual design and cost study utilizing some advanced concepts for a large MSBS which would be compatible with an 8-foot transonic wind tunnel and the highlights of the study are presented. Sverdrup Technology, Inc., recently performed a study under contract for Langley on the potential usefulness to the aerospace industry of a proposed large MSBS combined with a suitable transonic wind tunnel. The results of that study are discussed. Langley has partially funded the MSBS work at the University of Southampton for about 6 years under a grant arrangement and the major results are summarized.

NASA MAGNETIC SUSPENSION AND BALANCE SYSTEM

This is the official NASA logo used to identify the work in Magnetic Suspension and Balance Systems. It consists of a head-on view of a fighter-type aircraft model suspended in an octagonal test section of a wind tunnel without any mechanical model support. The model is surrounded by an artist's conception of magnetic field lines. A symbolic representation of a wind tunnel fan is shown outside of the test section.



OUTLINE

An outline of the presentation is shown in this figure. We will begin with some background by reviewing the reasons for the basic interest in the magnetic suspension of models in wind tunnels. The effects that can arise from mechanical model supports are well known to those with experience in performing aerodynamic tests in wind tunnels or in analyzing the resultant aerodynamic data. Some examples of model support problems that have been encountered in tests here at Langley will be presented. Model support interference is difficult to predict, especially at transonic speeds. It is very dependent on the particular subtleties of geometry of each different model configuration.

Magnetic suspension of the model in the wind tunnel test section is seen to be the only feasible solution for completely eliminating model support interference for three-dimensional models. Fourteen Magnetic Suspension and Balance Systems (MSBS) are known to have been constructed in this country and abroad since 1957. These MSBS have been used for wind tunnel tests in various facilities at speeds ranging from subsonic to hypersonic. However, the largest of these MSBS can only accommodate a test section that is 13 inches in diameter. Our aim of eliminating support interference for three-dimensional models in transonic wind tunnels requires us, therefore, to develop and to demonstrate the technology required for larger MSBS.

The NASA Langley effort in magnetic suspension involves three aspects. The first is the in-house work which is focused on the two magnetic suspension systems which are operational here at Langley. The second is the work that is accomplished through study contracts and the third is the research grant with the University of Southampton in England.

- Effects of mechanical model supports
- Examples of model support problems
- Solution - Magnetic Suspension and Balance System (MSBS)
- Goal - Develop technology required for larger MSBS
    - In-house work
    - Study contracts
    - Research grant
- Videotape

EFFECTS OF MECHANICAL MODEL SUPPORTS

The primary problem with mechanical model supports in wind tunnels arises from classical support interference. One source of the interference comes from alterations which have to be made to the model geometry to accommodate the model support or sting. In many cases, the aft fuselage must be enlarged or otherwise distorted for rear sting entry. The second source of support interference is the distorted flow pattern resulting from the physical presence of the model support or sting. Support interference increases with increasing tunnel pressure as the size of the model support structure must be made larger to accommodate the higher loads. In addition, as aircraft configurations become more sophisticated with higher and higher fineness ratios, the problems of support interference become more difficult. (For a bibliography on this subject, see ref. 1.)

The constraints imposed by mechanical model support systems make up the other class of problem areas. The first constraint which is listed is the limited movement normally available with a mechanical system both in translation and in rotation. The other constraints listed are related to dynamic testing. These include limits on the amount of dynamic motion and the difficulty in obtaining combined dynamic motions such as pitching and plunging. Also, it is often difficult to provide a dynamic motion about the correct center of gravity location for some vehicle configurations.

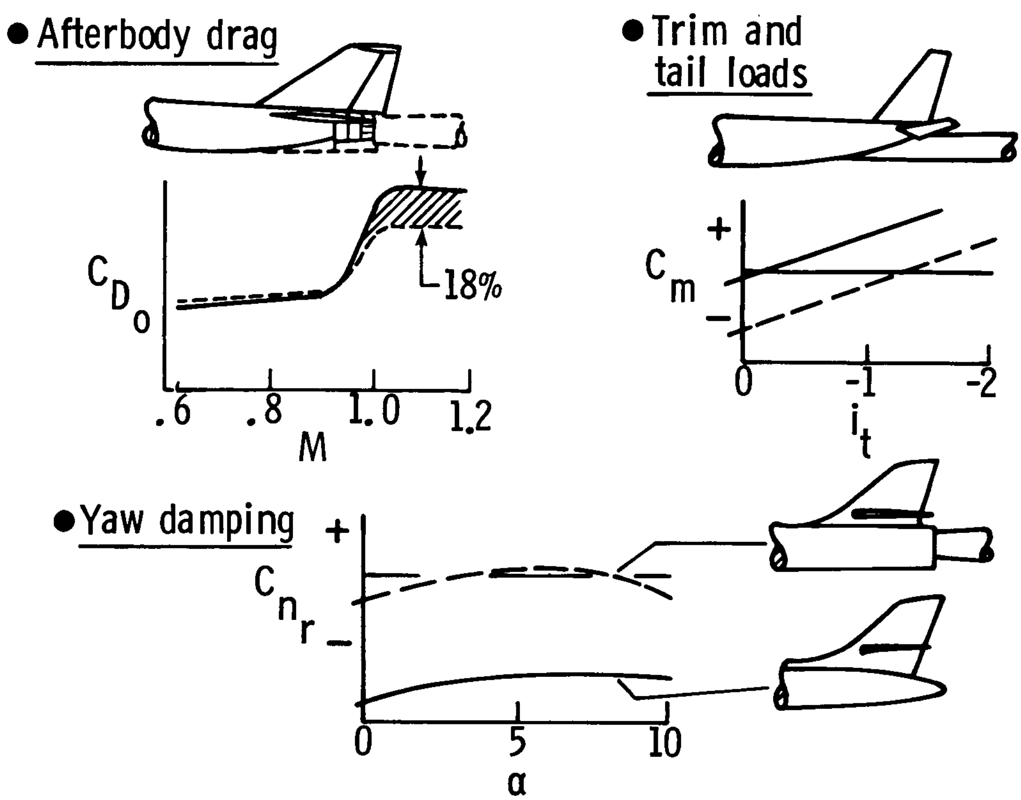
- Classical support interference (Bibliography-TM 81909)
    - Altered model geometry
    - Distorted flow
    - Increases with tunnel pressure
    - Increases with aircraft sophistication
- Support related restraints
    - Limited static motion (x, y, z, α, β, ϕ)
    - Limited dynamic motion (u, v, w, p, q, r; amplitudes)
    - Difficult to obtain combined motions
    - Difficult to obtain desired c. g. locations

EXAMPLES OF SOME MODEL SUPPORT PROBLEMS

This figure contains three typical examples of problems resulting from model support interference which have been encountered in tests in Langley wind tunnels. In the upper left of this figure, the sketch shows the true lines of the fighter-type aircraft with solid lines. The sting and the enlarged afterbody of the model required for the sting are shown as dashed lines. As indicated by the plot, the afterbody drag at transonic speeds, which accounts for a high percentage of the total drag, was found to be in error by about eighteen percent.

The sketch in the upper right portion of the figure illustrates a transport model mounted on a centerline sting. The proximity of the sting to the horizontal tail surfaces changed the flow pattern enough to give incorrect values of pitching moment versus tail incidence angle as shown for a constant angle of attack.

The two sketches at the bottom of the figure show how the boattailed rear fuselage of a model was enlarged to accommodate a sting for forced-oscillation dynamic stability tests. The measured damping in yaw at transonic speeds was found to be incorrect and even to have the wrong sign over part of the angle-of-attack range. This was caused by the proximity of the enlarged rear fuselage to the horizontal tail surfaces. Modifications had to be made to the model and the test program had to be repeated in a different facility with a smaller sting.



SOLUTION FOR SUPPORT INTERFERENCE

Magnetic suspension of the model is seen to be the only viable solution for three-dimensional testing of aircraft models in order to eliminate completely problems with model support interference. The concept was first demonstrated with a working system by the French in 1957. NASA Langley has been actively studying and sponsoring research on magnetic suspension ever since the publication of the original French technical paper. Abstracts of the known work published relative to Magnetic Suspension and Balance Systems (MSBS) for use in wind tunnels are contained in a 1983 bibliography (ref. 2). The report contains over 200 abstracts and is cross-indexed by subject, author, and corporate source. Reference 3 is an excellent summary of more recent developments.

Four MSBSs are known to be currently active and two out of the four are located here at this Center. One is the 13-inch system which has been on loan to NASA since 1979 from the U.S.A.F. Arnold Engineering Development Center (AEDC). It is the largest MSBS constructed to date, although the French have a system that is only slightly smaller, but not currently active. The 13-inch system was first operated in about 1965 and was later used with a hypersonic wind tunnel at AEDC. This system has been updated recently with a digital controller and an electro-optical position sensor system. The other MSBS, which is now operational at Langley, is the 6-inch system which was constructed by personnel of the MIT Aerophysics Laboratory under sponsorship of NASA and DOD. This system was first operated in 1969. Two unique features of this system are the sophisticated arrangement of the electromagnets and the Electromagnetic Position Sensor which operates as a differential transformer to sense model position. This system was acquired from MIT in 1982 when the Aerophysics Laboratory was closed and the system was just put back into operation here at Langley last year.

The other two MSBSs known to be active are located in England. The 7-inch system at the University of Southampton has been operational in various forms since 1964. Langley has partially supported the magnetic suspension work at Southampton since 1979 by means of a research grant. At the present time, this system is the most technically advanced in terms of capabilities such as an available angle-of-attack range of about sixty degrees. The 3-inch MSBS at Oxford University was recently being utilized to measure non-adiabatic wall effects on the drag of slender cone configurations at hypersonic speeds.

Since all of these MSBSs are relatively small, our research is directed towards the development and demonstration of the technology required for larger MSBS of a practical size for aerodynamic testing.

- Magnetic Suspension of the model is the only solution for 3-D testing
- Several small tunnels have operational MSBS
  - MSBS bibliography (TM 84661 - July 1983)
  - Four are active
    - 13 inch NASA/ AEDC
    - 6 inch NASA/ MIT
    - 7 inch University of Southampton
    - 3 inch Oxford University

AREAS OF ACTIVE RESEARCH

The areas of research currently being investigated in order to extend the usefulness of Magnetic Suspension and Balance Systems (MSBS) to larger sizes for wind tunnel applications are listed in the accompanying figure. A digital controller has been in operation with the Southampton 7-inch MSBS for several years and one was more recently put into operation with the 13-inch system here at Langley. However, the full potential of a digital controller must be further developed by optimizing the control algorithms. An ideal controller would be self-adaptive and, for example, would independently vary the loop gains with changes in model angle of attack and changes in test conditions.

Although many types of model position sensors have been developed, the "perfect" position sensor has not yet been devised. Also, it appears that for a fail-safe suspension system, redundant position sensing systems will be a necessity.

The areas of MSBS coil configuration design and the application of superconducting technology go hand-in-hand as any system for a test section larger than about two feet in diameter will of necessity have to use superconducting electromagnets. A 6-inch MSBS that used superconducting magnets was built and first operated in 1972 at the University of Virginia with Langley sponsorship. Superconducting electromagnets do have to be immersed in containers of liquid helium and kept at extremely low temperatures to maintain the operating state of essentially zero electrical resistance. In recent years, the use of superconducting electromagnets in such fields as high-energy physics research and in fusion research has matured this technology to the point where superconducting cable can be purchased "off-the-shelf."

The other areas listed on the figure as calibration, internal strain-gage balance, data accuracy, and data telemetry all fall into the very important category of items that must be well understood in order extract useful aerodynamic information from a magnetically suspended model. The concept of using a strain-gage balance inside the model both for load calibration and for the measurement of aerodynamic forces and moments was originated by Langley personnel. Frequency modulation telemetry has been used in the past, primarily by the French, but a new multichannel telemetry system being developed in-house will use an infrared light beam for data transmission.

- Digital controller
- Position sensing
- Coil configurations
- Application of superconducting technology
- Calibration
- Internal strain-gage balance
- Data accuracy
- Data telemetry

IN-HOUSE MSBS STATUS - APRIL 1985

The 13-inch NASA/AEDC system is currently being operated with a subsonic wind tunnel capable of about 0.5 Mach number. The system now has a digital controller in place of the original analog control system. Feedback control of the power amplifiers supplying the electromagnets must be used in all magnetic suspension systems in order to stabilize the model position. The X-ray position sensor originally developed by AEDC for the 13-inch system to fill a specific need has been replaced by an electro-optical system developed by the Langley Instrument Research Division that uses a small laser as the light source and self-scanning photodiode arrays as the sensing element. At the present time, the 13-inch system is being readied for load calibration. One method of doing this will be discussed in more detail later in the paper. As previously mentioned, there is also work in progress on the development of a telemetry system that will be used to transmit pressure and other data from a magnetically suspended model. Later this year, aerodynamic measurements will be made on the models listed in the figure. These tests will enable us to gain some practical testing experience with the system.

The 6-inch NASA/MIT system has been put back into operation complete with the subsonic tunnel that was built for the system at MIT. The Electromagnetic Position Sensor (EPS) which MIT originally developed for use with this system is a unique device. It operates as a differential transformer and is used to sense model position and attitude within the test section volume. The position and attitude information is required by the feedback control system and, of course, is also used for data reduction of the measured forces and moments. The Instrument Research Division is currently doing a complete calibration of the EPS to determine system accuracy, sensitivity, and repeatability. The EPS is a possible candidate for use in larger size suspension systems and an analysis is being made to determine if there are any inherent problems in scaling-up the EPS concept.

Model forces and moments in a MSBS are normally determined after suitable calibration from measurements of the current in each of the suspension electromagnets. An evaluation will be made of the practical data accuracy of both the 13-inch and the 6-inch systems. As previously mentioned, work is underway in developing alternate techniques of measuring model position and model loads.

13-inch NASA/ AEDC MSBS and subsonic wind tunnel

- System operational with digital controller
- Work in progress
  - System calibration
  - Telemetry development
- Aerodynamic measurements planned
  - Ogive-nose cylinder
  - Delta-wing model
  - Space shuttle orbiter

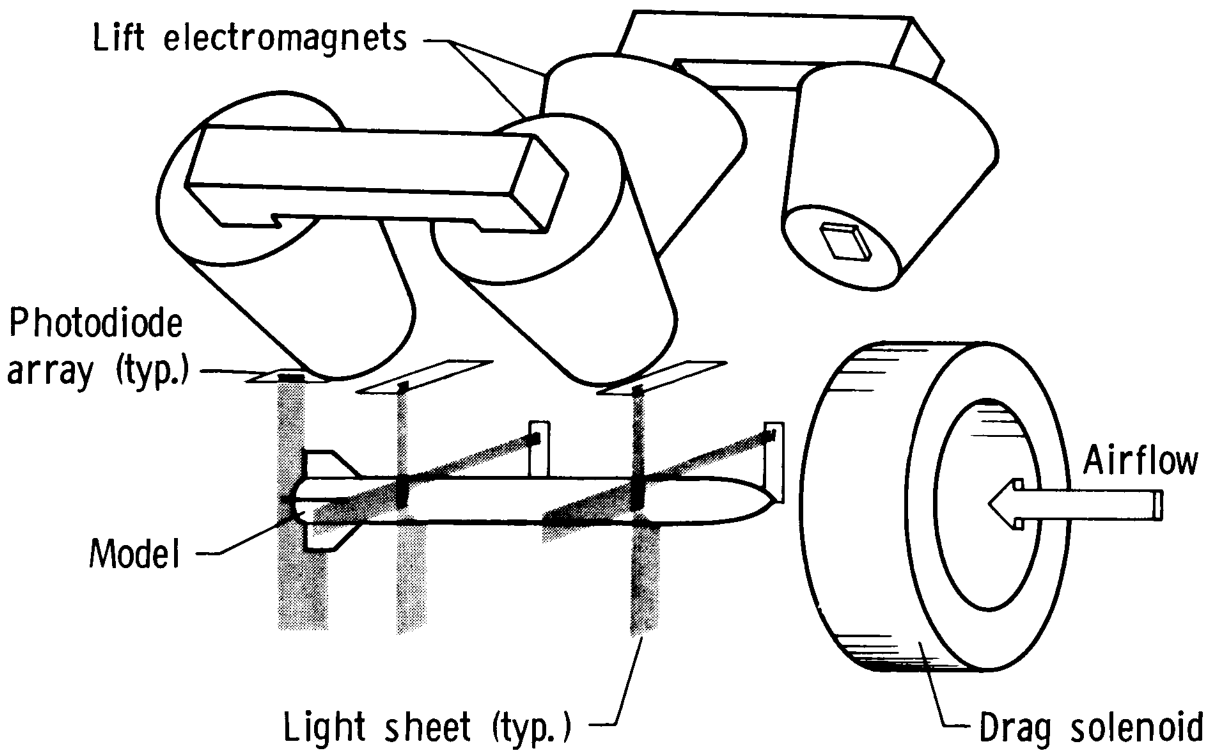
6-inch NASA/ MIT MSBS and subsonic wind tunnel

- Operational with Electromagnetic Position Sensor
- Evaluate practical MSBS data accuracy
- Develop alternate position and force measuring techniques

13-INCH NASA/AEDC MSBS

A sketch of the 13-inch system is shown in this figure. This system has the four lift electromagnets arranged in a "V" configuration. These four magnets provide the lift force, pitching moment, side force, and yawing moments. The drag solenoid provides the drag force. The test section for the subsonic wind tunnel is not shown in this sketch, but it passes through the drag solenoid. The model contains an iron core which, for a typical model, is normally about one inch in diameter and 6 inches long. The iron core is magnetized by the applied magnetic fields. The 13-inch MSBS has a lift force capability of a few pounds depending on the size of the iron core in the model.

The test section walls are made of clear plastic and the cross-section is a modified octagon that measures about 10.5 inches by 12.5 inches. The model position sensing system is made up of beams of light from three small lasers which, with the aid of suitable lenses and mirrors, are projected across the test section onto self-scanning photodiode arrays as illustrated in the sketch. The size of the light sheet incident on the photodiode arrays is dependent on the model position within the light sheet and the size of the shadow cast by the model.

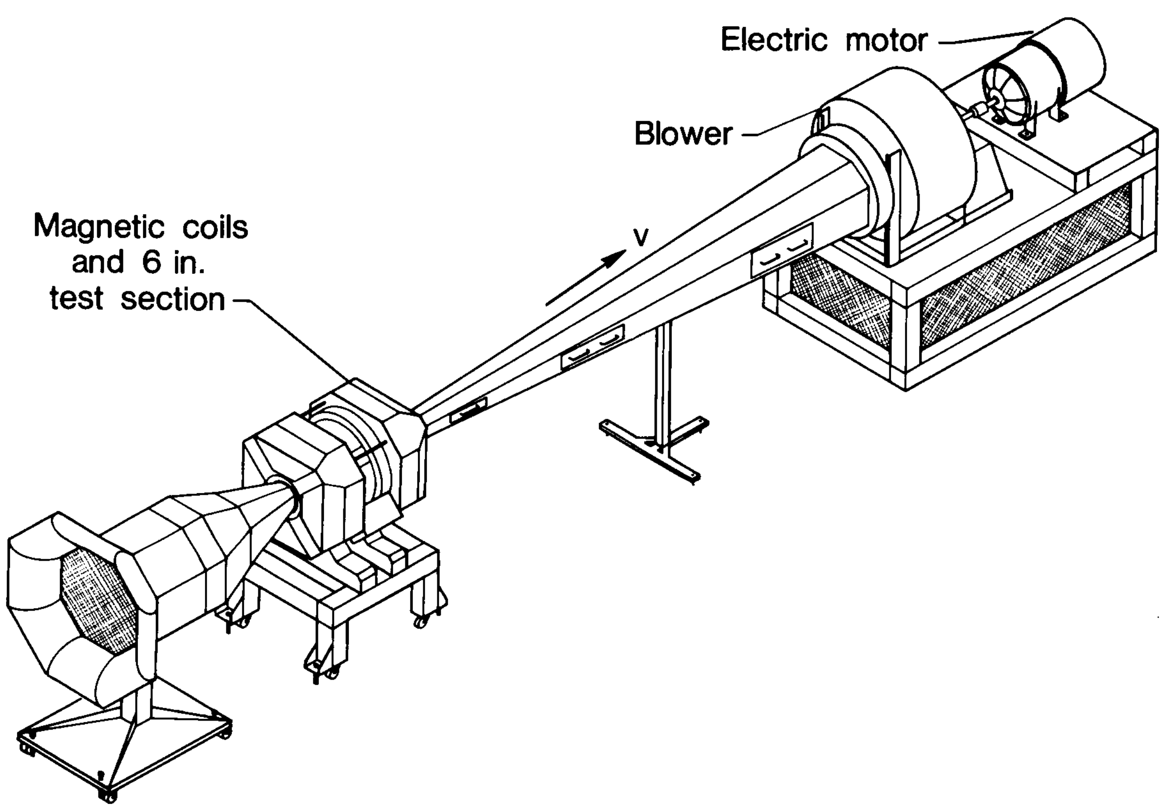


6-INCH NASA/MIT MSBS

This figure is a line drawing of the 6-inch MSBS which was acquired from MIT when the Aerophysics Laboratory was closed. The magnetic coils are contained within the cube-shaped housing which, for purposes of putting scale to the drawing, has a height of about 6 feet. The complete assembly including the subsonic tunnel is about thirty-five feet in length. Air is drawn into the tunnel bell-mouth through the test section and exhausts around the base of the blower back into the room. The associated power supplies and instrumentation racks are not shown in the drawing.

The electromagnets, which are water-cooled, are positioned around the outside of the volume containing the test section and the Electromagnetic Position Sensor (EPS) coils. Model viewing access is available through the sides of the coil housing. The EPS consists of an assembly of coils of fine wire, located immediately outside the walls of the clear plastic test section, and associated electronics. Magnetically soft iron is used for the model core and a pair of coils are dedicated to magnetizing the core.

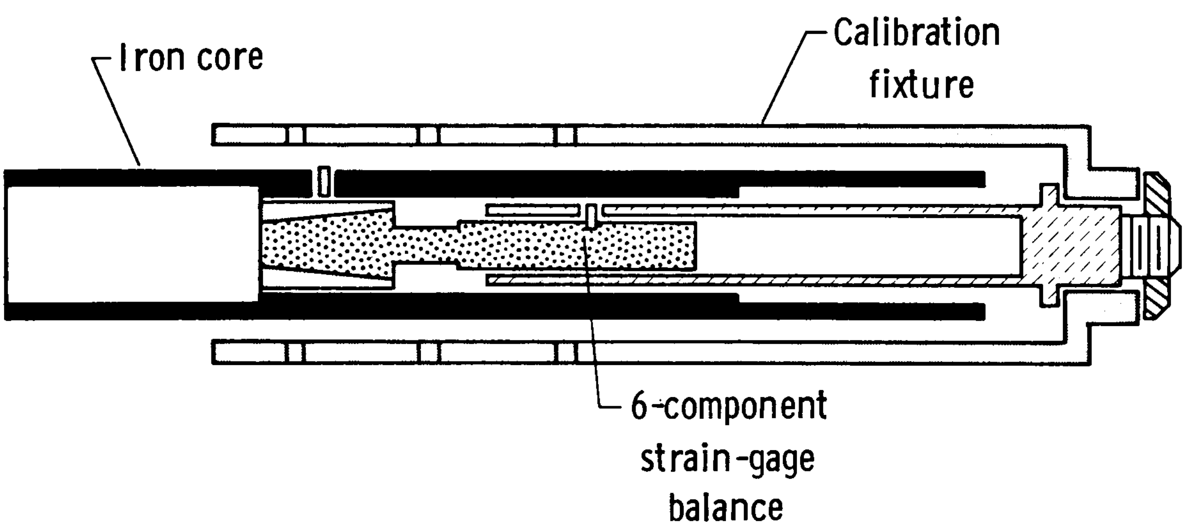
One of the last series of aerodynamic tests at MIT involved combined spinning and coning motions of some projectile shapes.



MSBS CALIBRATION MODEL

Force and moment data from a magnetic suspension and balance system have always been obtained in the past from measurements of the currents in the electromagnets. Accurate data can be obtained in this way, but it involves a tedious calibration process with each model core. Absolute model position must be maintained and model rotation in the pitch or yaw plane complicates the calibration process. To overcome some of these problems, personnel in the Langley Instrument Research Division have originated a concept of using an electrical resistance strain-gage balance to calibrate a magnetic suspension system. As illustrated in the sketch, the concept uses a strain-gage balance located between the iron core, which supports the assembly by the action of the magnetic fields, and the calibration fixture. Any load applied to the fixture is sensed by the strain-gage balance which has been calibrated previously using standard procedures for such balances. Initial tests in the 13-inch MSBS using hardware similar to that shown in the sketch were promising. Additional tests with strain-gage balances especially constructed with the correct size and load range are planned for both the 6-inch and the 13-inch MSBS.

Although this concept was originally devised just for wind-off calibration, it was later realized that the same concept can be used for aerodynamic data measurement if the calibration fixture in the sketch is replaced by an aerodynamic model. The internal strain-gage balance then can measure the resultant aerodynamic loads after the tare or weight loads are subtracted from the total loads. A telemetry system for transmitting the strain-gage balance data from the suspended model is being developed in order to demonstrate this capability. A similar strain-gage technique could also be used to measure loads on individual components such as on a wing or a canard.



FEASIBILITY STUDY

A study has been made by Madison Magnetics, Inc., under a contract from Langley to investigate the application of advanced concepts in superconducting technology to the design of a MSBS that would be compatible with a large transonic wind tunnel. For the purposes of the study, the specifications for the tunnel were arbitrarily set at an 8-foot by 8-foot test section operating at a Mach number of 0.9 and a stagnation pressure of one atmosphere. The model size and model loads were based on a highly maneuverable fighter design as this class of aircraft had been found to be a more difficult design problem when compared to other types of aircraft because of internal volume and load considerations. The required model angular displacement was ±30 degrees in pitch, ±10 degrees in yaw, and ±20 degrees in roll. Similar specifications were used in an earlier feasibility study in reference 4 by the General Electric Company, but that study was restricted to off-the-shelf equipment and technology.

The concept that had the most impact on the results of the Madison Magnetics study was the replacement of the usual iron core in the model with an isolated persistent superconducting solenoid. This concept was demonstrated at a small scale by researchers at the University of Southampton. The use of a superconducting core rather than an iron or permanent magnet core results in a larger magnetic moment in the model for an 8-foot size facility so that for the same loads the exterior electromagnets can be made smaller.

The most important conclusions from this study were that the combination of a compact model core superconducting solenoid and a unique coil arrangement was feasible and did meet the design requirements. The cost estimate for the construction of this system, not including the wind tunnel, was about $30 million.

This study has been published as reference 5. Further work by Madison Magnetics in refining and optimizing the design is underway.

- Application of advanced concepts
- Design and cost study
    - 8 ft × 8 ft test section
    - Mach = 0.9
    - Fighter-type model
- Conclusions
    - Design is feasible
    - Cost estimate about $ 30 million
- Further study under way

USEFULNESS STUDY

Sverdrup Technology, Inc., has made a study (ref. 6) for Langley which involved surveying the U.S. aerospace industry to determine if, in their opinion, current and future aerodynamic test requirements are sufficient to justify continued work by NASA on magnetic suspension systems for wind tunnels. In essence, the basic question revolved around the potential usefulness to the aerospace industry of a large tunnel fitted with a MSBS.

The approach taken was for the contractor to prepare a written description of the background and the capabilities of MSBS along with an appropriate questionnaire. This material was distributed to individuals in the industry. After the questionnaires were returned, follow-up visits were made for further discussion of all the material. A draft of the final report was prepared following evaluation and analysis of the results.

In summary, there was universal endorsement by the respondents for NASA to continue with its MSBS development program. The aircraft manufacturers, in general, were more enthusiastic than were the missile manufacturers. There was some concern expressed about facility cost and facility availability if only a single facility were to be constructed. A preference was noted for a large transonic MSBS facility as opposed to a midsized transonic, a midsized supersonic, or a large low-speed facility.

- Objective-survey U. S. aerospace industry
- Approach
    - Prepare description and capabilities
    - Distribute questionnaire
    - Follow-up visit and interview
    - Evaluate results
- Conclusions
    - Positive response for continued MSBS research
    - Some concern about facility cost and availability
    - Preference for large transonic MSBS facility
- Status
    - Draft of final report submitted

RESEARCH GRANT

The University of Southampton in England has been very active and productive in magnetic suspension research for many years. The work has been partially supported since 1979 by a NASA research grant to investigate the technology required for large systems. The 7-inch MSBS at Southampton has been operational in several configurations since 1964. The latest configuration has full digital control of the model through a minicomputer in all six degrees of freedom. The bipolar power supplies used with the electromagnets in the 7-inch system are the type that were developed for commercial use with numerically controlled machinery. The symmetrical coil configuration, along with the digital controller and the bipolar power supplies, has allowed the researchers at Southampton to demonstrate a model pitch angle of 60 degrees. This extreme angle of attack capability was shown in a videotape at the conclusion of the presentation. Theoretical computations have not shown any restrictions on an unlimited attitude capability.

As mentioned previously, the concept of the superconducting model core has been demonstrated at Southampton with a working version that met the design requirement of a 30 minute "flying" time. The superconducting model core shows great promise of lowering the cost of large systems by providing a larger magnetic moment in the model than would be possible with a conventional iron core.

- 7-inch MSBS
- Concepts studied and demonstrated
  - Digital controls
  - Bi-polar power supplies
  - Symmetrical coil configuration
  - High angle of attack capability
  - Superconducting model core

CONCLUSIONS

Support interference is the basic problem that arises from the use of mechanical model supports in wind tunnels. Magnetic suspension of the model is the only viable solution for three-dimensional testing of aircraft models in order to eliminate completely model support interference. All of the basic technology for a large Magnetic Suspension and Balance System (MSBS) has been demonstrated at small scale and design studies have shown that a large MSBS is feasible. A survey of the U.S. aerospace industry has shown a positive response for NASA to continue with its MSBS development program. Work is progressing on preliminary engineering designs for a large MSBS and the cost estimates for a large MSBS appear to be reasonable.

- Support interference is a problem
- Magnetic suspension only solution for 3-D testing
- Basic technology has been demonstrated at small scale
- Large MSBS feasible
- Positive industry response for continued MSBS development
- Work progressing on engineering design for large MSBS
- Cost estimates for large MSBS appear reasonable

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